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More about Bat "Radar"

A sequel to an earlier article which described the capacity of bats to locate objects by supersonic echoes. This natural sonar is now known to incorporate extraordinary refinements

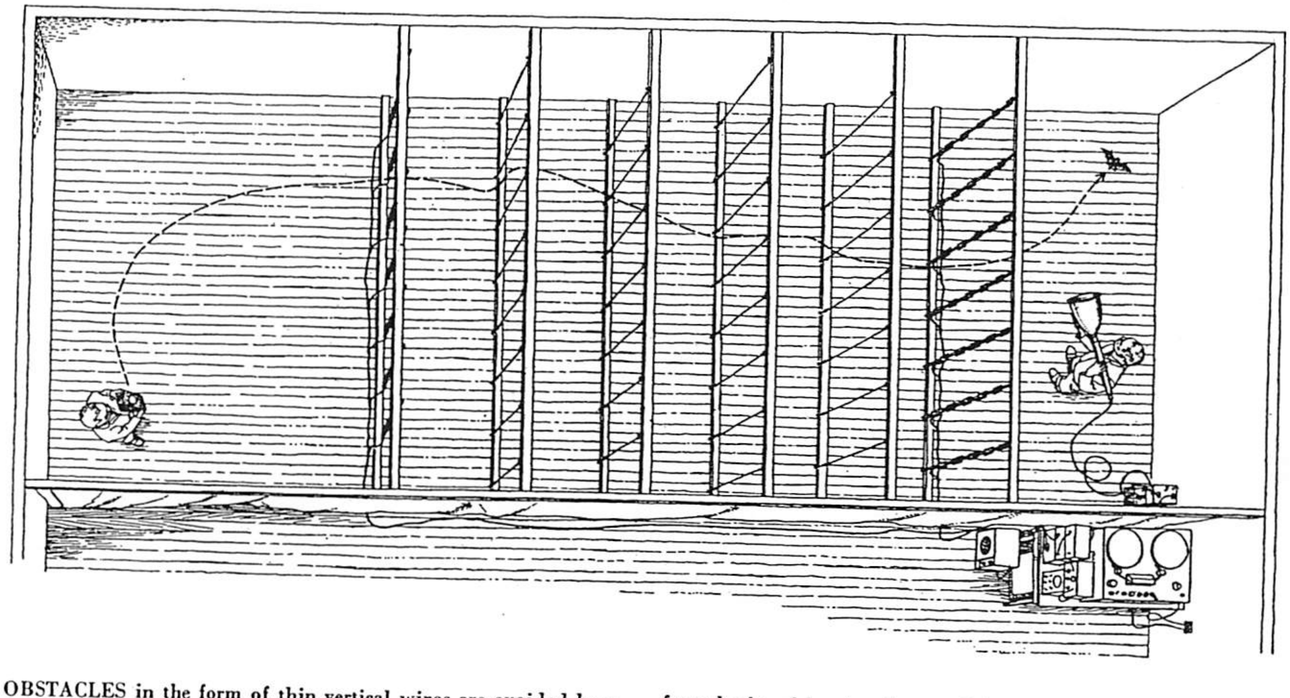
by Donald R. Griffin

In these days of technological triumphs it is well to remind ourselves from time to time that living mechanisms are often incomparably more efficient than their artificial imitations. There is no better illustration of this rule than the sonar system of bats. Ounce for ounce and watt for watt, it is billions of times more efficient and more sensitive than the radars and sonars contrived by man [*see table at bottom of page 42*].

Of course the bats have had some 50 million years of evolution to refine their sonar. Their physiological mechanisms for echolocation, based on all this accumulated experience, should therefore repay our thorough study and analysis.

To appreciate the precision of the bats' echolocation we must first consider the degree of their reliance upon it. Thanks to sonar, an insect-eating bat can get along perfectly well without eyesight. This was brilliantly demonstrated by an experiment performed in the late 18th century by the Italian naturalist Lazaro Spallanzani. He caught some bats in a bell tower, blinded them and released them outdoors. Four of these blind bats were recaptured after they had found their way back to the bell tower, and on examining their stomach contents Spallanzani found that they had been able to capture and gorge themselves with flying insects in the field. We know from experiments that bats easily find insects in the dark of night, even when the insects emit no sound that can be heard by human ears. A bat will catch hundreds of soft-bodied, silent-flying moths or gnats in a single hour. It will even detect and chase pebbles or cotton spitballs tossed into the air.

In our studies of bats engaged in insect-hunting in the field we use an apparatus which translates the bats' high-pitched, inaudible sonar signals into audible clicks. When the big brown bat (*Eptesicus fuscus*) cruises past at 40 or 50 feet above the ground, the clicks sound like the slow put-put of an old marine engine. As the bat swoops toward a moth, the sounds speed up to the tempo of an idling outboard motor, and



OBSTACLES in the form of thin vertical wires are avoided by a bat despite the presence of interfering noise. The noise comes from banks of loudspeakers to left and right of the four sets of wires. Man at right holds microphone which picks up bat's signals.

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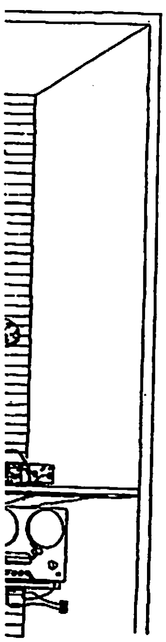

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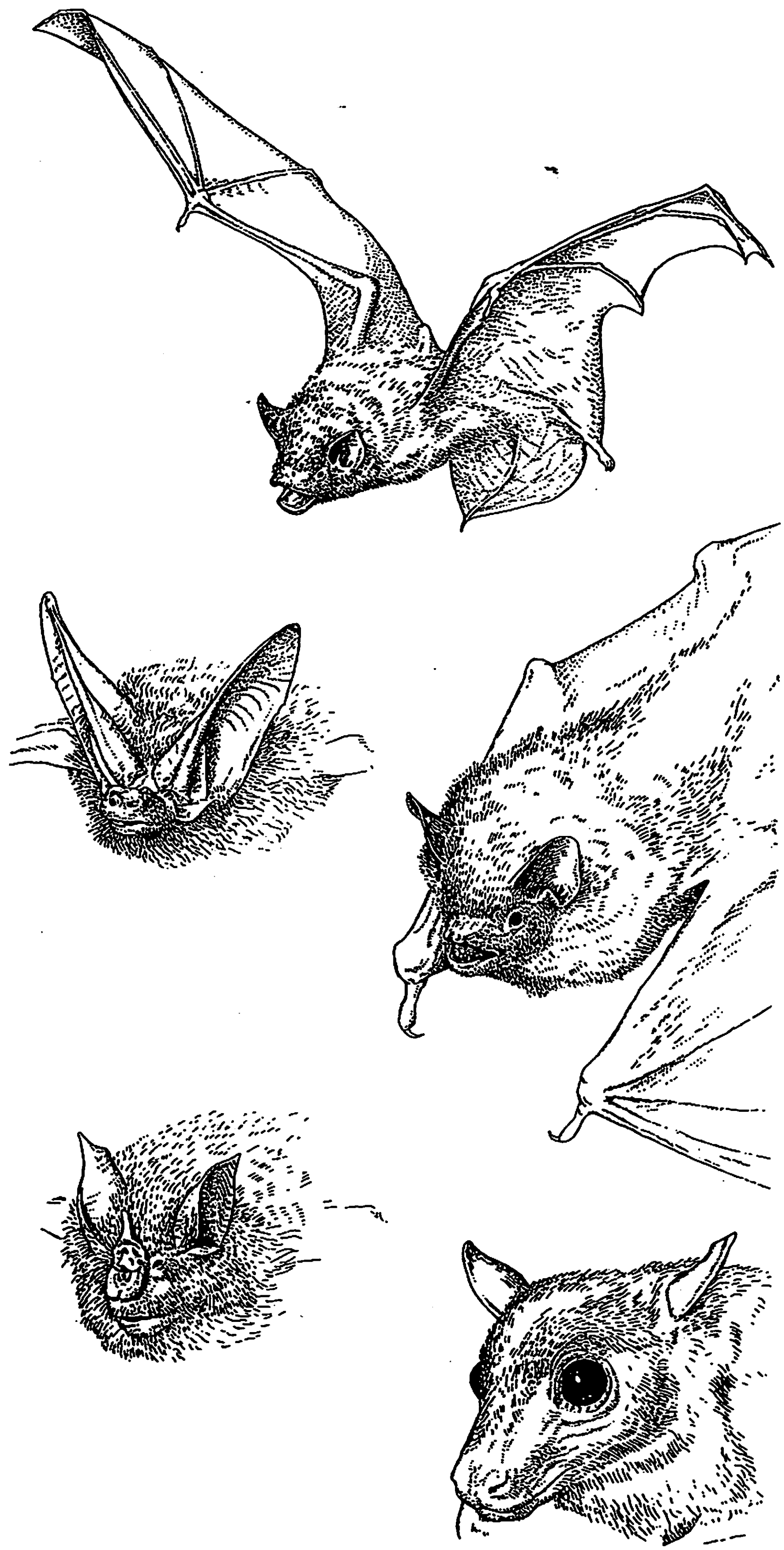
when the chase grows really hot they are like the buzz of a model-airplane gasoline engine. It seems almost certain that these adjustments of the pulses are made in order to enable the bat to home on its insect prey.

At the cruising tempo each pulse is about 10 to 15 thousandths of a second long; during the buzz the pulses are shortened to less than a thousandth of a second and are emitted at rates as high as 200 per second. These sound patterns can be visualized by means of a sound spectrogram [*see charts on page 43*]. Within each individual pulse of sound the frequency drops as much as a whole octave (from about 50,000 to 25,000 cycles per second). As the pitch changes, the wavelength rises from about six to 12 millimeters. This is just the size range of most insects upon which the bat feeds. The bat's sound pulse may sweep the whole octave, because its target varies in size as the insect turns its body and flutters its wings.

The largest bats, such as the flying foxes or Old World fruit bats [see "Bats," by William A. Wimsatt; SCIENTIFIC AMERICAN, November, 1957], have no sonar. As their prominent eyes suggest, they depend on vision; if forced to fly in the dark, they are as helpless as an ordinary bird. One genus of bat uses echolocation in dark caves but flies by vision and emits no sounds in the light. Its orientation sounds are sharp clicks audible to the human ear, like those of the cave-dwelling oil bird of South America [see "Bird Sonar," by Donald R. Griffin; SCIENTIFIC AMERICAN, March, 1954].

On the other hand, all of the small bats (suborder *Microchiroptera*) rely largely on echolocation, to the best of our present knowledge. Certain families of bats in tropical America use only a single wavelength or a mixture of harmonically related frequencies, instead of varying the frequency systematically in each pulse. Those that live on fruit, and the vampire bats that feed on the blood of animals, employ faint pulses of this type.

Another highly specialized group, the horseshoe bats of the Old World, have elaborate nose leaves which act as horns to focus their orientation sounds in a sharp beam; they sweep the beam back and forth to scan their surroundings. The most surprising of all the specialized bats are the species that feed on fish. These bats, like the brown bat and many other species, have a well-developed system of frequency-modulated ("FM") sonar, but since sound loses much of its energy in passing from air into water and *vice*



BATS shown in these drawings all use some type of echolocation system except for the fruit bat *Rousettus*, which appears at bottom right. The other species represented are the small brown bat *Myotis lucifugus* (*top*), the long-eared bat *Plecotus* (*left center*), the large brown bat *Eptesicus* (*right center*) and the horseshoe bat *Rhinolophus* (*bottom left*).

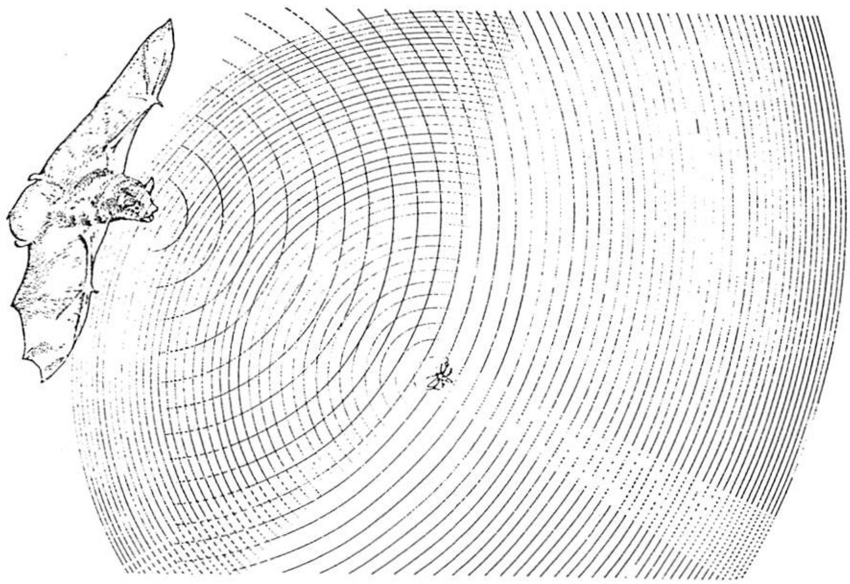
versa, the big puzzle is: How can the bats locate fish under water by means of this system?

Echolocation by bats is still such a new discovery that we have not yet grasped all its refinements. The common impression is that it is merely a crude collision warning device. But the bats' use of their system to hunt insects shows that it must be very sharp and precise, and we have verified this by experiments in the laboratory. Small bats are put through their maneuvers in a room full of standardized arrays of rods or fine wire. Flying in a room with quarter-inch rods spaced about twice their wingspan apart, the bats usually dodge the rods successfully, touching the rods only a small percentage of the time. As the diameter of the rods or wires is reduced, the percentage of success falls off. When the thickness of the wire is considerably less than one tenth the wavelength of the bat's sounds, the animal's sonar becomes ineffective. For example, the little brown bat (*Myotis lucifugus*), whose shortest sound wavelength is about three millimeters, can detect a wire less than two tenths of a millimeter in diameter, but its sonar system fails on wires less than one tenth of a millimeter in diameter.

When obstacles (including insect prey) loom up in the bat's path, it speeds up its emission of sound pulses to help in location. We have made use of this fact to measure the little brown bat's range of detection. Motion pictures, accompanied by a sound track, showed that the bat detects a three-millimeter wire at a distance of about seven feet, on the average, and its range for the finest wires it can avoid at all is about three feet. Considering the size of the bat and of the target, these are truly remarkable distances.

Do the echoes tell the bat anything about the detected object? Some years ago Sven Dijkgraaf at the University of Utrecht in the Netherlands trained some bats to distinguish between two targets which had the form of a circle and a cross respectively. The animals learned to select and land on the target where they had been trained to expect food. Bats can tell whether bars in their path are horizontal or vertical, and they will attempt to get through a much tighter spacing of horizontal bars than of vertical bars. In gliding through a closely spaced horizontal array the bat must decide just how to time its wingbeats so that its wings are level, rather than at the top or bottom of the stroke, at the moment of passage. All in all, we can say that bats obtain a fairly detailed acoustic "picture" of their surroundings by means of echolocation.

Probably the most impressive aspect of the bats' echolocation performance is their ability to detect their targets in spite of loud "noise" or jamming. They have a truly remarkable "discriminator," as a radio engineer would say. Bats are highly gregarious animals, and hundreds fly in and out of the same cave within range of one another's sounds. Yet in spite of all the confusion of signals in the same frequency band, each bat is



INSECT IS LOCATED by means of reflected sound waves (*colored curves*). Variation in the spacing of the curves represents changing wavelength and frequency of the bat's cry.

	BAT	RADARS		SONAR
	EPTESICUS	SCR-268	AN/APS-10	QCS/T
RANGE OF DETECTION (METERS)	2	150,000	80,000	2,500
WEIGHT OF SYSTEM (KILOGRAMS)	.012	12,000	90	450
PEAK POWER OUTPUT (WATTS)	.00001	75,000	10,000	600
DIAMETER OF TARGET (METERS)	.01	5	3	5
ECHOLOCATION EFFICIENCY INDEX	2×10^{9}	6×10^{-5}	3×10^{-2}	2×10^{-3}
RELATIVE FIGURE OF MERIT	1	3×10^{-14}	1.5×10^{-11}	10^{-12}

COMPARISON of the efficiency of the bat's echolocation system with that of man-made devices shows that nature knows tricks which engineers have not yet learned. "Echolocation efficiency index" is range divided by the product of weight times power times target diameter. "Relative figure of merit" compares the echolocation efficiency indexes with the bat as 1.

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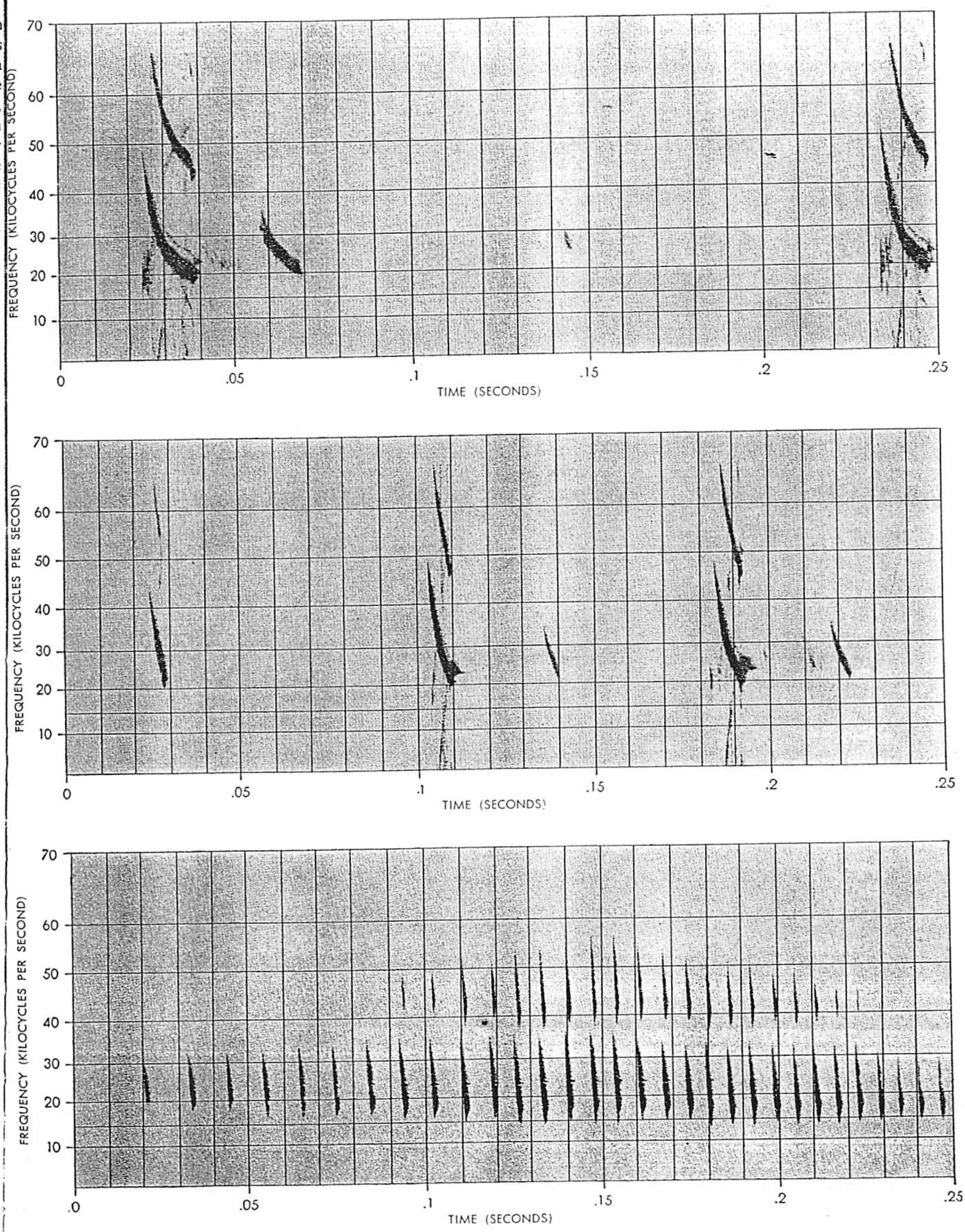
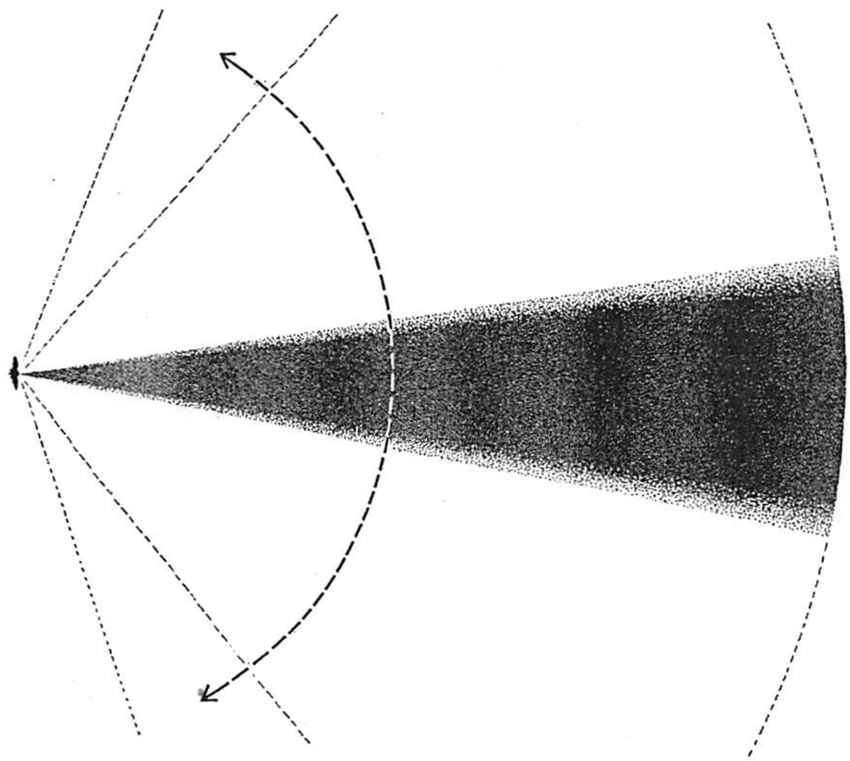


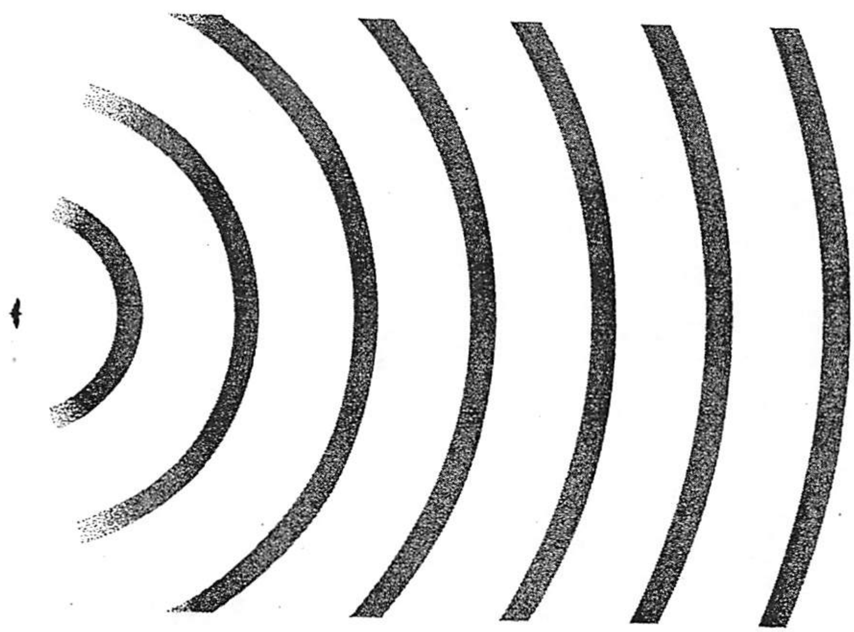
ORIENTATION SOUNDS of the large brown bat were recorded as slanting traces in these spectrograms while the animal was cruising (*top*), beginning pursuit of an insect (*middle*) and closing in on its prey (*bottom*). The traces appearing at .06 seconds in the top spectrogram and at .14 and .22 seconds in the middle spectrogram are echoes, which probably come from nearby buildings.

able to guide itself by the echoes of its own signals. Bats learned long ago how to distinguish the critically important echoes from other distracting sounds having similar properties.

We have recently tested the bats' discriminatory powers by means of special loudspeakers which can generate intense sound pulses. We found that a continuous broad-band noise which all but drowned out the bats' cries did not disorient them. They could still evade an insect net with which one tried to catch them; they were able to dodge wires about one millimeter in diameter; they landed wherever they chose.



NARROW BEAM which sweeps back and forth is emitted by horseshoe bat in hunting insects. Beam is about 20 degrees wide, has a constant frequency and a pulse length of 50 feet.



WIDE BEAM of short, frequency-modulated pulses is emitted by most bats while hunting. Each pulse (*gray curves*) is about 1.5 feet long. Beam is fixed with respect to bat's head.

In some experiments A. D. Grinnell and I did succeed in jamming certain FM bats, but it was not easy, and the effect was only slight. We worked on a species of lump-nosed bat (*Plecotus rafinesquii*) which emits comparatively weak signals. With two banks of loudspeakers we filled the flight room with a noise field of about the same intensity as the bats' echolocation signals. The more skillful individual bats were still able to thread their way through an array of one-millimeter wires spaced 18 inches apart. Only when we reduced the wires to well below half a millimeter in diameter (less than one tenth the wavelength of the bats' sounds) did the bats fail to detect the wires.

To appreciate the bats' feats of auditory discrimination, we must remember that the echoes are very much fainter than the sounds they emit—in fact, fainter by a factor of 2,000. And they must pick out these echoes in a field which is as loud as their emitted sounds. The situation is dramatically illustrated when we play back the recordings at a reduced speed which brings the sounds into the range of human hearing. The bat's outgoing pulses can just barely be heard amid the random noise; the echoes are quite inaudible. Yet the bat is distinguishing and using these signals, some 2,000 times fainter than the background noise!

Much of the modern study of communication systems centers on this problem of discriminating information-carrying signals from competing noise. Engineers must find ways to "reach down into the noise" to detect and identify faint signals not discernible by ordinary methods. Perhaps we can learn something from the bats, which have solved the problem with surprising success. They have achieved their signal-to-noise discrimination with an auditory system that weighs only a fraction of a gram, while we rely on computing machines which seem grossly cumbersome by comparison.

When I watch bats darting about in pursuit of insects, dodging wires in the midst of the nastiest noise that I can generate, and indeed employing their gift of echolocation in a vast variety of ways, I cannot escape the conviction that new and enlightening surprises still wait upon the appropriate experiments. It would be wise to learn as much as we possibly can from the long and successful experience of these little animals with problems so closely analogous to those that rightly command the urgent attention of physicists and engineers.